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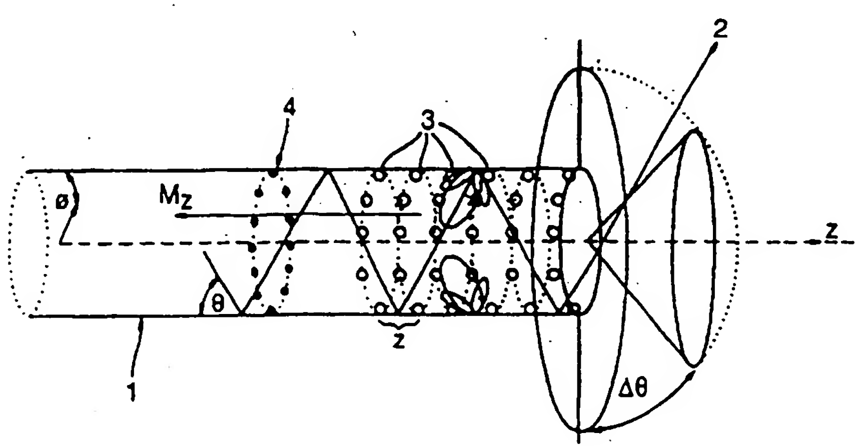
(54) Abstract Title
**Method and apparatus for the active control of sound radiated from flow ducts**

(57) A method for the active control of sound radiated in a duct (1) comprising sensing sound from an array (4) of sensors located on the inside surface of a flow duct and controlling an array (3) of secondary sources (loudspeakers) so as to minimize sound radiated in the far field. This is done by controlling the sound sources so as to minimize a cost function. Depending on whether total sound power or sound power towards the sideline is to be reduced, different cost functions are used by the method.

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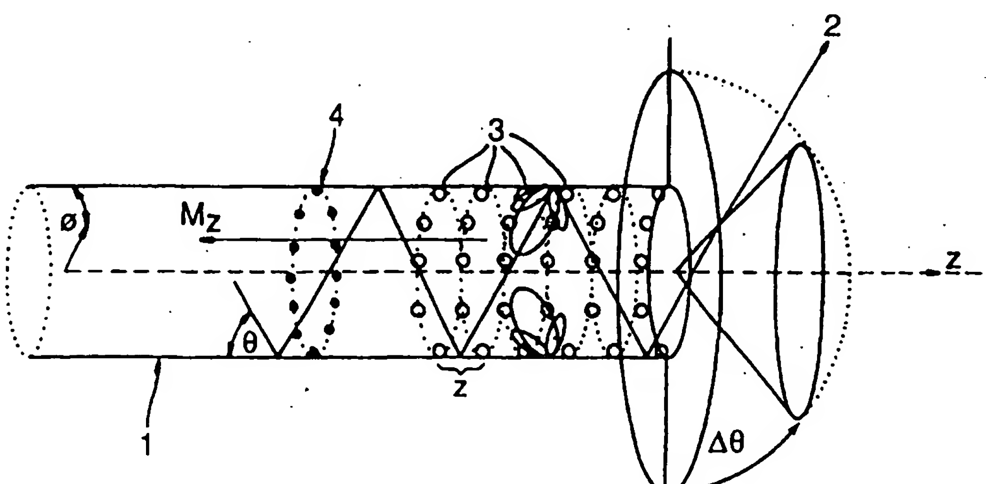


**(57) Abstract**

A method for the active control of sound radiated in a duct (1) comprising sensing sound from an array (4) of sensors located on the inside surface of a flow duct and controlling an array (3) of secondary sources (loudspeakers) so as to minimize sound radiated in the far field. This is done by controlling the sound sources so as to minimize a cost function. Depending on whether total sound power or sound power towards the sideline is to be reduced, different cost functions are used by the method.

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# METHOD AND APPARATUS FOR THE ACTIVE CONTROL OF SOUND RADIATED FROM FLOW DUCTS

The invention relates to the active control to limit harmonic sound radiated towards the sidelines from ducts containing a subsonic, uniform flow. It is in particular applicable to limitation of noise radiated from circular ducts such a gas turbine intake.

There is growing interest in applying active noise control to reduce the fan tones radiated from aircraft turbo fan intakes, prompted by increasingly strict legislation regulating noise levels in populated areas. The traditional approach of sound proofing is to line the air inlet with sound absorbing material. However with the increasing trend towards shorter inlet required for the higher efficiency of high bypass ration engines, there is less space for the sound proofing material to be located.

An alternative approach in recent years has been to investigate active noise control. Patent applications WO 95/19075 and WO 94/08540 both describe active controllers for flow ducts having internally located sensors and sound sources. No details however are given of the control algorithm. Patent US 5355417 discloses a configuration for the active control of aircraft engine inlet noise by including an array of circumferentially arranged sound sources mounted inside an inlet duct as well as an array of sensors arranged in a ring. Again the active control algorithm is not disclosed in any great detail. Moreover the results of this system show an increase in sound propagated towards the sidelines, which are the important regions for sound reduction.

Using external sensors, the inventors have determined a clear relationship between reductions in the radiated far field acoustic pressure in the radiated far field (in the region well away from the duct) and corresponding reductions in the internal transmitted field inside the duct. This provided relationships that allowed the use of internal sensors and internal sources to reduce noise levels in the far field towards the sidelines in a controlled and determined fashion. In other words an obtainable quantity at the duct wall has been determined which is a function of acoustic pressure, which has a robust and stable relationship to the far field acoustic pressure for the important range of radiation angles that contribute most to the annoyance of those living beneath the flight path.

It is an objective of the invention to provide both an active noise control arrangement and a method to be implemented which reduces the fan tones radiated from the intake of turbofan engines in the sidelines.

According to the invention is provided a duct for fluid flow having means for active control of sound

radiated therefrom, said duct comprising sound sensors located on the inner surface of said duct and grouped together in one or more planes transverse with respect to the duct axis, and at least one secondary source whose operation is a function of sound received at said sound sensors characterised in that the axial spacing of said transverse planes is not more than $0.5\lambda_{min}(1+M_{zmax})$ where $\lambda_{min}$ is the wavelength corresponding to the radiated tone frequency of interest and $M_{zmax}$ is the maximum Mach number of the free stream flow in the duct.

By using sensors external to the engines to observe directly the far field radiated sound the inventors have determined a method to controls loudspeakers, or so called secondary sources, so as to minimise engine noise in the far field.

The invention also provides a method for the active control of sound radiated from a fluid flow duct comprising:

a) sensing sound from an array of sensors located on the inside surface of the duct and

b) controlling an array of secondary sources located on the inside surface of the duct, so as to minimise sound radiated in the far field in a pre-set band of angles to the duct axis, characterised in that only sound propagated within a pre-set angular interval to the duct axis is effectively sensed and used to control the operation of said secondary sources.

Further the inventors have determined a relationship between the internal and external fields which has been incorporated into a cost function which, upon minimisation, has the desired effect of producing sound pressure level reduction in chosen radiation angles. Manipulation of the in-duct acoustic pressure as a result of the observation can be used to minimise transmitted sound and therefore far field sound.

More specifically it relates to a line array of in-duct wall mounted discrete sensor elements whose pressure signals can be processed to provide an estimate of transmitted sound field with propagation angle. This measurement has been shown to be closely related to the variation in the radiated field versus polar angle. The internal sound field at the sensor elements is used for controlling the radiated field in the important range of radiation angles towards the sidelines. The important aspect of the induct error sensing methods proposed here is the simplicity of the algorithm used.

Advantages of the method are the simplicity and generality to all circular flow ducts since the proposed algorithms only require the fan tone frequency of interest and the speed of the free stream flow as input variables.

The invention will be described with reference to the following figures of which:

Figure 1 shows a schematic diagram of a circular duct containing uniform axial flow, comprising an array of sensors and secondary sources.

Figure 1b shows the relationship between resultant wavenumber km. normal to the localwavefront. the propagation angle $\theta_{mn}$ and axial wavenumber $k_{zmn}$.

Figure 2 shows the a typical variation of axial wavenumber with propagation angle with the ideal receiver response.

Figure 3 shows the directivity function of a ten element liiie array at the design frequency steered at 45° for zero Mach number and Mach number equal to -0.5.

Figure 4 shows comparisons at ka=20 of the reduction in sound pressure level versus polar angle averaged over azimuth with external sensors and internal sensors for and Mz=0 respectively using 18 regularly spaced sources.

Figure 5 shows the change in modal amplitude verses propagation angle following the minimisation of the sum of squared signal at ten equally spaced line arrays comprising ten elements, each forming beams in the directions between 60° and 90° in 5° increments. in the example in figure 4.

Figure 6 shows comparisons at ka=20 of the reduction in sound pressure level versus polar angle averaged over azimuth with external sensors and internal sensors for M. = -0.5 respectively using 18 regularly spaced sources.

Figure 7 shows the change in modal amplitude verses propagation angle following the minimisation of the sum of squared signal at ten equally spaced line arrays comprising ten elements. each forming beams in the directions between 30° and 60° in 5° increments. for the example of figure 5.

Figure 8 shows the relationship between phase velocity. croup velocity and intake axial flow velocity in aduct.

Figure 9 shows an unflanged hard walled duct containing a subsonic intake flow.

Noise from aircraft cause annoyance in populated areas. For an aircraft on approach and during takeoff these noise radiation angles are well away from the duct axis, towards the sidelines. Reference to the term "control bandwidth" means the band of angles (measured from 90° to the duct axis) over which the radiated sound is to be minimised. The relationship between transmitted and radiated sound fields has been determined, which allow a method of active control to be formulated in order to reduce the radiated sound power in a band of angles towards the sidelines. Matching the dimensions of the control region to the typical beamwidths of the principal far field radiation lobes produces reductions in the transmitted sound field in a continuous band of propagation angles. Modes whose main radiation lobe is in this band are nearest cut - off and are characterised by steep propagation angles relative to the duct axis.

Thc invention uses e.g. one or more circumferential arrays of appropriately phased sensors at the duct wall that can observe the acoustic pressure associated with those propagation angles that are responsible for the field radiated towards the sidelines.

Before describing the implementation of the invention, the formulation of the relationship between reductions in the radiated far field and reductions in the internal, transmitted field are shown and terms are hereinafter defined. Most of the other terminology is familiar to the person skilled in the art.

Figure 1a represents a circular, hard walled flanged duct (1) containing uniform, axial flow of Mach No. of $M_z$ (2). A ray-mode of acoustic pressure (sound) (2) transmitted along the duct and then radiated from the duct intake is shown and can be detected by a wall mounted line array, of appropriately phased (located) sensors (3). The figure shows the relationship between resultant wavenumber $k_{mn}$ normal to the local wavefront, the propagation angle $\theta_{mn}$ and axial wavenumber $k_{zmn}$. The symbol k designates acoustic wavenumber $k=2\pi f/c$ where f is the sound frequency and c is the speed of sound. The in-duct 'error' sensing principle proposed here is based on the mode angle $\theta_{mn}$ which specifies the angle between the modal wavefront and the duct axis. More importantly the mode angle $\theta_{mn}$ in the duct, for both flanged and unflanged ducts, is also coincident with the angle of the principal lobe of far field radiation providing there is zero flow external to the duct. Even when the flow speeds inside and outside the duct are different, a unique and monotonic relationship exists between the transmission and radiation angle. Much of the original mode-ray angle information pertaining to the transmitted sound field inside the duct is therefore preserved in the radiated sound field. The duct also contains one or more secondany sources (4) preferably, as angular arrays, the control of which is dependent upon the received signals of the sensors.

The sensors are arranged in the figure as a series of annular rings. However the method is not limited to

such an arrangement. and may include any suitable spacing e.g. the sensors may not form rings but may be clustered closer together over a small sector of the duct wall.

Initial studies revealed the performance of a single circumferential array of up to 20 wall mounted secondary sources whose strengths were determined in order to minimise the sound power radiated from the intake that passes across a hypothetical far field surface which subtends a band of radiation angles to the duct axis. Performance predictions were obtained over a frequency range of $0 \leq ka \leq 25$ for a 6m long duct of 1.5m radius with intake flow corresponding to a Mach number $M_z$ = -0.5. The secondary source array was located at a single axial location 2m from the face of the duct intake. Reduction in the amplitude of modes with the greatest propagation angle are responsible for sound power reductions in this desired band of radiation angles that are directed towards the sidelines. The different responses of the modal amplitudes found with and without flow can be attributed to an increased number of modes that can propagate in a mean flow and to a diminished range of propagation angles that follow compared to that no mean flow.

It was deduced that increased number of modes can propagate in axial, mean flow compared with no flow, and this results in diminished range of propagation angles. By contrast, with flow, the amplitudes of the majority of modes that propagate close to the duct axis, such as the plane wave, are increased, resulting in an increase in sound pressure level at radiation angles in the forward directions. These are not a significant contributor to community annoyance due to the very long propagation distances to the ground. Initial modelling detennined that secondary sources are not required to reproduce sensitive phase changes which affect a number of modes.

The following mathematically quantifies the relationship between the modal axial wavenumber and the angle between the modal wavefront and the duct axis in circular. hard walled ducts containing a uniform. axial flow. This relationship will be found in later sections to be central to the design of the in-duct sensor array. The mathematics also sheds light on the preferred design features of the invention.

The acoustic pressure in a circular duct satisfies the convected form of the wave equation written below in cylindrical co-ordinates.

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r^2}\frac{\partial^2}{\partial\phi^2}+\frac{\partial^2}{\partial z^2}\right)p(a,\phi,z,t)=\left(\frac{1}{c}\frac{\partial}{\partial t}+M_z\frac{\partial}{\partial z}\right)^2 p(a,\phi,z,t) \qquad (1)$$

where the coordinate system is defined in figure 1. $M_z$ is the Mach number of the flow and $c$ is the

ambient sound speed. This wave equation is defined such that $M_z < 0$ at the duct intake. At sufficiently high $ka$, reflected sound at the duct termination is negligible. The complete solution to this equation for harmonically time varying sources in a circular flow duct, neglecting reflections, has the separable form

$$p(a,\phi,z,t) = \exp\{j\omega t\}\sum_{m,n} \bar{p}_{mn}(z_s)J_m(k_{rmn}r)\exp\{j(-k_{Zmn}(z-z_s)+m\phi)\} \qquad (2)$$

where $\bar{p}_{mn}$ and $k_{Zmn}$ denote the modal amplitude and the axial wavenumber associated with modes propagating towards the duct exit and $z_s$ is the axial location of the source. In a hard walled duct the radial eigenvalues $k_{rmn}$ equals $j'_{mn}/a$, where $j'_{mn}$ denotes the n[th] zero of $j'_{mn}$ and $a$ is the duct radius.

Substituting this solution back into the wave equation yields the following dispersion relationship

$$k_{rmn}^2 + k_{Zmn}^2 = (k - M_z k_{Zmn})^2 \qquad (3)$$

where $k$ is the free space wavenumber $w/c$. $k_{rmn}$ actually represents a combined radial-circumferential wavenumber. The resultant wavenumber in the duct $k_{mn}$ is therefore equal to $k - M_z k_{Zmn}$. The angle $\theta_{mn}$, which specifies the angle between the modal wavefront and the duct axis, is calculated from $\cos\theta_{mn} = k_{Zmn}/k_{mn}$ thus

$$\cos\theta_{mn} = \frac{k_{Zmn}}{k - M_z k_{Zmn}} \qquad (4)$$

Equation (4) can be re-arranged to express the axial wavenumber of the $(m,n)^{th}$ mode in terms of the propagation angle as

$$k_{Zmn} = \frac{-k\cos\theta_{mn}}{1 + M_z\cos\theta_{mn}} \qquad (5a)$$

$$k_{mn} = \frac{-k}{1 + M_z\cos\theta_{mn}} \qquad (5b)$$

A geometric interpretation of these wavenumbers and their relationship to the modal propagation angle is illustrated in figure lb. A surprising aspect of equation (5b) is its independence of the duct radius $a$. This

is not the case for the ray mode angles in the radial and circumferential directions which vary quite strongly with $u$.

The external. far field acoustic pressure due to the $(m,n)^{th}$ mode from a flanged duct may be written in the form

$$p_{mn} = \bar{p}_{mn} D_{mn}(k,\theta)\frac{\exp\{j(\omega t + m\phi - kR)\}}{R} \quad (6)$$

where $D_{mn}$ denotes the directivity function of the $(m,n)^{th}$ mode and $R$ is the distance from the duct face to the observer.

$$D_{mn}(k,\theta) = \frac{jk\left(J_{m-1}(ka\sin\theta) - J_{m+1}(ka\sin\theta)\right)}{k_{rmn}^2 - k^2\sin^2\theta} \quad (7)$$

Expressing $\theta_{pmn}$ in terms of the axial wavenumber with the aid of the dispersion relation of equation (3) for $M_z = 0$ gives

$$\theta_{pmn} = \cos^{-1}\left(k_{Zmn} / k\right) \quad (8)$$

This describes the essential monotonic and unique relationship between the axial propagation angle $\theta_{mn}$ of a mode in the duct.

A wall mounted phased line array for the detection of modes by modal angle $\theta_{mn}$. Modal amplitude reductions that result from reducing the sound power radiated in a band of angles towards the sidelines has been shown to bear a definite and causal relationship to reductions in the in-duct sound field transmitted obliquely to the duct axis. The objective is therefore to design a wall mounted sensor array comprising of a relatively small number of discrete sensors that has sufficiently good directivity to detect this change in the transmitted sound field. Since modes can only be controlled if they can be observed. the ideal receiver response is plotted in figure 4 and is a step function which detects only the signals arriving at large incidence angles to the array while rejecting signals transmitted at angles close to the duct axis. Also plotted in figure 4 is the typical variation of axial wavenumber with propagation angle from equation (5a). Figure 4 therefore demonstrates that the ideal receiver characteristics is a high pass filter of propagation angle which. by virtue of equation (5). is also a low pass filter of axial wavenumber.

It shows a typical variation of axial wavenumber with propagation angle and the ideal receiver response.

A simple sensor array whose directivity characteristics approximates to the ideal step function response illustrated in figure 4 will now be described. The relationship between axial wavenumber and propagation angle given by equation (5a) can be used to express the acoustic pressure at some circumferential location $\phi$ at the duct wall $r = a$ such that

$$p(a,\phi,z) = \sum_{m,n} p_{mn}(a,\phi,z_s)\exp\left\{\frac{jk(z - z_s)\cos\theta_{mn}}{1 + M_z\cos\theta_{mn}}\right\} \qquad (9)$$

The pressure signals at an axial line array of sensors at the duct wall due to the internal transmitted sound field is therefore indistinguishable from a series of plane waves arriving at the modal propagation angles. To be able to discriminate all possible modal arrival angles (or more precisely spatial frequency) without ambiguity, the minimum sensor separation distance $Dz$ is required to be, as a consequence of the Nyquist sampling theorem, one half the wavelength of the highest axial spatial frequency in the flow. According to equation (5a), this is the plane wave mode (corresponding to $\theta_{00} = 0$) transmitted at the highest frequency of interest $f_{max}$ in the highest intake flow speed of interest $M_{Zmax}$. The highest frequency in general corresponds to the highest harmonic $s_{max}$ of the blade passing frequency of interest $f_{max} = s_{max}\Omega b$, where $\Omega$ is the shaft rotational frequency, and $b$ is the number of rotor blades. From equation (5a),

$$\Delta z = \tfrac{1}{2}\lambda_{min}(1 + M_{Z\max}) \qquad (10)$$

where $\lambda_{min} = c/f_{max}$ which is the shortest wavelength in the radiation field. The frequency, $f_{max}$ is known as the design frequency of the array. If $z_l$ denotes the axial position of the first sensor in a wall mounted line array comprising $L$ elements separated by a distance $\Delta z$, the $l^{th}$ sensor is required to have the axial location $z_l$ given by,

$$z_l = z_1 + (l - 1)\Delta z \qquad (11)$$

the acoustic pressure $p(a,\phi,z_l)$ at the $l^{th}$ sensor can therefore be written in the form

$$p(a,\phi,z_l) = \sum_{m,n} p_{mn}(a,\phi,z_s)\exp\left\{j(\delta_{mn} + l\psi_{mn})\right\} \qquad (12)$$

where $\delta_{mn}$ is simply a phase term that is constant across the array. thus

$$\delta_{mn} = \frac{k(z_1 - z_1 - \Delta z)\cos\theta_{mn}}{1 + M_z \cos\theta_{mn}} \tag{13}$$

and $\psi_{mn}$ is the relative phase angle between adjacent sensors

$$\psi_{mn} = \frac{\pi(f/f_{max})(1 + M_{Z\max})\cos\theta_{mn}}{1 + M_z \cos\theta_{mn}} \tag{14}$$

In order to prevent ambiguity in the measured arrival angle caused by aliasing. therefore, a fundamentally important condition is that $f \le f_{max}$. Equation (12) effectively specifies the complex weights $w_l(\theta_0)$ of a simple 'delay and add' line array beam former. In order to preferentially amplify the acoustic pressure signal arriving at angle $\theta_0$ to the line array,. the array elements are simply required to delay the signals at each sensor by an appropriate amount $\Psi_0(\theta_0)$ which upon addition, causes the signals at each sensor to be summed perfectly in-phase. The beam steer angle are made such that they are made to scan the angles θ from 90° to 90° to 90° -Δθ in some appropriate incremental angle. By inspection of equation (12), therefore, the $l^{th}$ element in the linc array is required to have the phase specified by

$$w_l(\theta_0) = \exp\{-jl\psi_0(\theta_0)\} \tag{15}$$

where $\theta_0$ is the beam steer angle

$$\psi_0 = \frac{\pi(f/f_{max})(1 + M_{Z\max})\cos\theta_0}{1 + M_z \cos\theta_0} \tag{16}$$

This formula is a fundamental result which enables the invention to be implemented and allows a method for devising a directional wall mounted receiver simply by locating the axial line array of sensors with a maximum separation distance equal to $\Delta z = \frac{1}{2}\lambda_{min}(1 + M_{Zmax})$ and by introducing the relative time delays between the sensors specified by equations (19) and (20). It is generally applicable to all circular ducts. irrespective of radius and depends only on the Mach number of the free stream flow and the frequency of the fan tone to be controlled. Both these parameters can be readily determined.

Sensor line array directivity (beam steer angles)

The followmg describes relationships between the sensor (receiver) line array directivity characteristics and its relationship to mode detection.

The directivity characteristics of the sensor (receiver) line array can be described by the normalised directivity function $d(\theta/\theta_0)$. This function specifies the array response at some angle $\theta$ when the main beam is steered at an angle $\theta_0$, and can be determined from

$$d(\theta/\theta_0) = \frac{1}{L}\sum_{l=1}^{L}\exp\{-jl(\psi - \psi_0)\} \qquad (17)$$

and is defined such that $d(\theta/\theta_0) = 1$. Equation (21) is a geometric series that can be summed over $L$ terms to give

$$d(\theta/\theta_0) = \frac{1}{L}\frac{\sin(L(\psi - \psi_0)/2)}{\sin((\psi = \psi_0)/2)} \qquad (18)$$

In terms of the propagation angle, $\psi - \psi_0$, mav be written as

$$\psi - \psi_0 = \pi(f/f_{max})(1 + M_{z\,max})\left(\frac{\cos\theta}{1 + M_z \cos\theta} - \frac{\cos\theta_0}{1 + M_z \cos\theta_0}\right) \qquad (19)$$

By way of example, comparisons of the directivity functions evaluated at the design frequency $f_{max}$ at Mach numbers of 0 and -0.5 for an array comprising ten elements steered at 45° to the array axis is presented in figure 5. Figure 3 shows the directivity function of a ten element line array at the design frequency, steered at 45° for zero Mach number (solid line) and with a Mach number equal to -0.5 (dashed line). For this particular receiver array the 10dB beamwidth is about 20°. The presence of flow with speed equal to $M_z$ = -0.5, which is typical for an aircraft on approach, appears to cause no appreciable change in directivity characteristics apart from a slight narrowing of the main beam and a reduction in the number of side lobes. The important difference is that to achieve roughly the same beamwidth in this flow speed, a ten element array at the design frequency has a shorter length of just $2.25\lambda_{min}$ which is half the array length necessary in a duct without flow according to equation (14). For this reason it would appear, therefore, that the presence of intake flow, having the property of contracting

the spatial frequencies by virtue of an effectively reduced sound speed. is advantageous. For example. at the comparatively low frequency of 500Hz. ($ka$ = 13 for $a$ = 1.5m) the optimal length of a ten element array at the duct intake at the design frequency is about 1.5m. A reasonably long array with good directivity can therefore be fitted. quite easily. within modern high by - pass ratio engines. At more realistic blade passing frequencies. that are typically greater than 500Hz. the array lengh is even shorter.

The output $b(\theta_0,a,\phi)$ of a receiver array located at an azimuthal angle $\phi$ at the duct wall $r = a$ and steered at an angle $\theta_0$ is obtained from the following operation on the discrete wall pressure measurements

$$b(\theta_0,a,\phi)=\sum_{l=1}^{L} w_l(\theta_0)p(a,\phi,z_l) \tag{20}$$

where the acoustic pressure at each sensor is the sum of ray - modes according to equation (12) so that

$$b(\theta_0,a,\phi)=\sum_{m,n} p_{mn}(a,\phi,z_s)\exp\{j\delta_{mn}\}\sum_{l=1}^{L}\exp\{jl(\psi_{mn}-\psi_0)\} \tag{21}$$

The summation of terms over $l$ can be evaluated exactly to give

$$b(\theta_0,a,\phi)=L\sum_{m,n}\frac{\sin(L(\psi_{mn}-\psi_0)/2)}{\sin((\psi_{mn}-\psi_0)/2)}p_{mn}(a,\phi,z_s)\exp\{j\delta_{mn}\} \tag{22}$$

which is precisely the directivity function $Ld(\theta_{mn}/\theta_0)$ of the receiver line array deduced in equation (22). The receiver output can therefore be written as

$$b(\theta_0,a,\phi)=L\sum_{m,n} d(\theta_{mn}/\theta_0)p_{mn}(a,\phi,z_s)\exp\{j\delta_{mn}\} \tag{23}$$

The effect of implementing this receiver array is to weight the modal contributions to the receiver by a factor equal to the array's directivity function $d(\theta_{mn}/\theta_0)$ evaluated at the modal arrival angle $\theta_{mn}$. Steering of the array's main beam in the direction of the mode angles closest to cut-off will therefore amplify the acoustic pressure propagating with those angles highlighted in figures 2 and 3 as being directly responsible for the reductions in the important band of radiation angles. i.e. those towards the sidelines. The transmitted sound field whose propagation angles are diffracted outside the control region. i.e.. close to the duct axis. will be partially rejected at the receiver by an amount depending on the

degree of side lobe suppression compared to the main beam according to equation (23). The ability of the receiver array to discriminate between different modal propagation angles will depend on the angular bandwidth of the transmitted sound field in which pressure reductions arise, in relation to the beamwidth of the array. Greater rejection of the signals due to the unwanted arrival angles will be achieved when the ray modes are well separated in propagation angles.

Implementation of the invention for far field active control using in-duct fine array error sensors.

The above describes relationships between the in-duct pressure field and how they effect the acoustic pressure in the far field. The above analysis has shown how best to glean in-duct sensor data to estimate far field effects. This enables the skilled man to optimally design the sensor array including beam steer angles and the use of general parameter such as duct flow speed to estimate far field radiated pressure. The important point here is the ability to quantify the effect of changes in the in-duct field to changes in the far field. From initial calculations sound power reductions at radiation angles towards the sidelines is accompanied by well defined changes to the transmitted sound field and that the change in the angular variation of the transmitted field was detectable by a line array receiver at the duct wall comprising relatively few sensors.

In this section the use of these sources to implement the invention is described whereby control of secondary sources (loudspeakers) arranged in the duct are suitably operated from data of the sensors to optimally minimise sound at a particular fan tone frequency. The secondary sources will be driven to minimise the sum of squared signals each signal being produced by steering a beam formed by a number of independent axial sensors line array located around the duct wall; this brings about a similar modification to the transmitted field as that produced by conventional external far field error sensors, in order to procure similar reductions in the radiated field. This is done by using the algorithms set out below.

If $K$ line arrays each produces $I$ signals by steering of the beams at $I$ angles, a suitable cost function J is given by

$$J = \sum_{i=1}^{I} \sum_{k=1}^{K} \left| b(\theta_{0i}, a, \phi_k) \right|^2 \quad (24)$$

where $b(\theta_{0i}, a, \phi_k)$ denotes the complex signal produced after steering a beam at an angle $\theta_{0i}$ by a receiver

array located at the circumferential angle $\phi_k$ around the duct wall and is computed from

$$b(\theta_{0l}, a, \phi_k) = \sum_{l=1}^{L} w_l(\theta_{0l}) p(a, \phi_k, z_l) \qquad (25)$$

From hereon the dimensions of the wall mounted sensor array will be denoted by $(K, L)$ so that the total number of error sensors is $K$ x $L$. The function $J$ in equation (24) call be expanded to produce a quadratic function of the secondary source strengths. The vector of optimal secondany source strengths that uniquely and globally minimises $J$ can be deduced by standard mathematical methods. Note that it is desirable to have as many sensors as possible in the axial direction to provide good receiver directivity, and as many line arrays around the duct wall as possible to ensure that $J$ is minimised.

Figure 4 shows tests of the in-duct receiver array's ability to control the radiated sound towards the sidelines is from a duct without flow. A 10 x 10 sensor array is used comprising ten line array receivers equally spaced around the duct wall, each consisting of ten elements. The beams at each of the receivers are steered in the range of angles from 55° to 90° from the duct axis in increments of 5°. Eighteen secondary sources are driven to minimise the sum of squared signals produced by the ten independent receivers according to equation (24). A comparison between the radiated far field sound pressure level reductions, obtained by computer simulation versus polar angle produced by using the internal and external sensors is shown. These results represent the average reduction over twenty azimuthal angles. The solid curve is the result of minimising the sound power radiated into a band of angles from 55° to 90° from the duct axis using a dense grid of external error sensors in the control region that afford perfect observability of the radiated field. As a result of the measurements from the sensors located inside the duct, loudspeaker or sources can be driven to minimise the noise in the far field. Figure 5 shows the change in modal amplitude verses propagation angle following the minimisation of the sum of squared signal at ten equally spaced line arrays comprising ten elements, each forming beams in the directions between 60° and 90° in 5° increments. The agreement between the two curves is extremely good. Sound power reduction in the control region using the in-duct receiver array is 17.9dB which compares very well with the theoretical maximum of 21.6dB obtained by the external sensors. Both in-duct and external error sensing strategies produce the necessary, and very similar transformations in the transmitted sound field.

Increasing the dimensions of the array to (20,20), requiring a total of 400 microphones, affords a further increase in sound power reduction to 20.6dB. Although the number of sensors is unrealistically large in this case, this simulation serves to validate further the principle underlying the proposed control

technique. However. increasing the number of sensors indefinitely does not produce reductions arbitrarily close to the theoretical maximum since one is ultimately limited by the optimal phase relationships between the modes. The proposed sensing technique does not allow this manipulation of the modes. The significance of the phase in the control mechanism. while comparatively unimportant at high *ka*. is important when the number of propagating modes is small. i.e.. at low *ka*. Nevertheless. substantial pressure reductions are still achievable at these low frequencies.

The same performance comparison of the change in sound pressure level versus polar angle between using the internal and external error sensors was repeated at $ka = 15$ with a flow speed of $M_z = -0.5$ and is presented in figure 6. A ring of fifteen secondary sources were driven to minimise $J$ comprising signals produced by the (10,10) sensor array forming beams steered at 30° to 60° to the duct axis in 5° increments. These beam steer angles differ from the previous no flow example to take account of the modified propagation angles due to the flow. As before. the two results agree to an extremely good degree. The sound power reduction in the control bandwidth is 10.5dB which is just 3dB below theoretical maximum reduction of 13.4dB obtained using far field sensors. However. the effect on the transmitted field produced by the two approaches is slightly different. although the broad mechanism of control which consists of reducing the modal amplitudes closest to cut-off remains the same. Figure 7 shows the change in modal amplitude verses propagation angle following the minimisation of the sum of squared signal at ten equally spaced line arrays comprising ten elements. each forming beams in the directions benveen 30° and 60° in 5° increments. for the case in figure 5.

A large number of sensors is required to construct the array. About one hundred is anticipated to be necessary, although many more would of course be desirable. However the large number of sensors required does not translate to a correspondingly high processing bandwidth. The reason for this is the independence of the line arrays which is fundamental to ensuring robustness of the technique. One is not required to measure transfer functions between sensors on different line arrays. Each receiver line array could therefore be allocated its own dedicated processor for forming the beams whose output could then be input to a main processor for real time adaptation of the secondary sources.

Another important constraint on the receiver array arises from the importance of sensing only the in-duct propagating field. which contains all the information contained in the far field radiation. and not the evanescent field close to the sources which transports very little energy to the radiated far field. The sensor element nearest the sources must therefore be separated by several acoustic wavelengths in order to avoid contamination of the measured signals by the non-propagating field.

A further issue relates to which beam steer angles gives best reductions in far field noise level. The relationship between the propagation and radiation angles in real turbo fan engines will certainly be much more complicated than that suggested here: ray mode angles are complicated by complex geometry of the nacelle, shear velocity and temperature profiles present across the duct. However in all cases from elementary acoustics a unique, monotonic correspondence exits between the angle of the ray mode at the duct and the radiated angle of the far field peak pressure maximum, allowing the in-duct sensing technique of the invention to be successful and widely applicable.

By minimising the sum of squared signals produced by a number of identical, independent line arrays equally spaced around the duct wall, each forming beams at the appropriate angles, a similar modification to the transmitted sound field (radiated far field) is obtained by the invention. Using the internal sensor array gave reductions in the radiated sound power tosvards the sidelines which was within a few decibels of the theoretical maximum reduction obtained given perfect observability of the radiated field. Significantly, these sound power reductions were achieved without the knowledge of transfer functions between sensors on different line arrays; the technique is therefore likely to be stable and robust by virtue of its simplicity.

The beam steer angles that afford the best reduction in radiated pressure towards the sidelines are therefore very difficult to predict in real turbofans. However, it is envisaged that in practice the best combination of beam steer angles, number of secondary sources and number of line arrays etc. which afford the greatest reduction in noise will be determined from the results of a number of systematic fly-by tests.

The sensor array should be preferably located flush to the duct walls in order not to interfere with the passage of flow through the engine.

<u>Relationship between in-duct propagation angle and the far field radiation angle</u>

The use of the sensor array is fundamentally dependent on the existence of a unique and simple relationship between the transmitted sound field and the radiated far field. The cost functions to be minimized depend on whether total sound power or sound pressure towards the sidelenes is to be reduced. In order to enable these cost functions, which are given hereinafter and hereinbefore, to be implemented, basic relationships and definitions are given. The sensor array described here is designed to detect the modes based on their different axial propagation angles $\theta_{m\mu}$. By simple geometry this angle

is also given by:

$$\theta_{m\mu} = \frac{c_{m\mu}}{c_0} \qquad (26)$$

where $c_{m\mu}$ denotes the modal phase speed and may be regarded as a vector normal to the modal wavefront. A more fundamental variable is the angle with which acoustic energy is transmitted along the duct and this is related to the axial group velocity $c_{gm\mu}$, where

$$c_{gm\mu} = \frac{d\omega}{dk_{Zm\mu}} \qquad (27)$$

Perfoming the differentiation of the dispersion relation of equation (3) yields the following relationship between the axial phase and group velocities

$$c_{gm\mu} = c_{m\mu} + c_0 M_z \qquad (28)$$

The angle with which acoustic energy is transmitted along the duct is identical to the angle of the mode peak pressure far field radiation lobe $\theta_{Pm\mu}$ when the flow speed inside and outside the duct are equal. Thus,

$$\theta_{Pm\mu} = \frac{c_{m\mu} + c_0 M_z}{c_R} \qquad (29)$$

where $c_R$ is the resultant sound speed in the direction of sound power propagation. This result is readily derived since the sound speed in the radial and circumferential direction are unchanged by the presence of flow. A sketch indicating the relationship between the phase and group velocities is provided by figure 8 for the case when the flow speed is the same everywhere.

The angle $\theta_{Pm\mu}$ of the modal peak pressure radiation

$$\zeta_{m\mu} = \frac{k\sqrt{1 - M_z^2}}{k_{rm\mu}} \qquad (30)$$

This angle is given by:

$$\cos\theta_{Pm\mu} = \left( \frac{\left(1 - M_z^2\right)\left(1 - 1/\zeta_{m\mu}^2\right)}{1 - M_z^2\left(1 - 1/\zeta_{m\mu}^2\right)} \right)^{1/2} \tag{31}$$

which allows comparison with the expression for $\theta_{m\mu}$ in terms of the cut-off ratio

$$\cos\theta_{m\mu} = \frac{-M_z + \sqrt{1 - 1/\zeta_{m\mu}^2}}{1 - M_z\sqrt{1 - 1/\zeta_{m\mu}^2}} \tag{32}$$

Thus, the in-duct axial propagation angle $\theta_{m\mu}$ which can be detected using the in-duct sensor array, and the radiated peak far field pressure angle $\theta_{Pm\mu}$, are connected by the above two equations with cut-off ratio as the independent parameter.

The angle of the modal peak far field pressure radiation lobe is closely related to the axial propagation angle. The deviation between the two angles increases with increasing Mach number. The range of axial propagation angles becomes smaller with increasing intake Mach number whereas the range of the principal radiation lobe angles remains distributed between 0° for the plane wave mode and 90° at cut-off, irrespective of flow speed.

Reducing transmitted and radiated sound power

The active minimisation of the total transmitted sound power was found to be particularly effective in reducing levels at the fundamental of the blade passing frequency. However, sound power was not found to be an appropriate cost function when reducing sideline radiation is the main objective, although there may be occasions when reducing the sound power may be desirable. For uncoupled modes the sound power transmitted in the flow duct could be written as:

$$W = \sum_{m\mu} \gamma_{m\mu} \left|\bar{b}_{m\mu}\right|^2, \qquad \gamma_{m\mu} \geq 0 \tag{33}$$

where $\gamma_{m\mu}$ is the real part of an effective modal admittance in the flow calculated from

$$\gamma_{m\mu} = \left(1 + M_z^2\right)\mathrm{Re}\left\{\beta_{m\mu}\right\} + M_z\left(1 + |\beta_{m\mu}|^2\right) \qquad (34)$$

where $\beta_{m\mu}$ is the modal admittance

The real part of the effective modal admittance in the flow appears to be closely correlated to the modal propagation angle $\theta_{m\mu}$, and tends to zero as the mode approaches cut-off. ie., $\gamma_{m\mu} \rightarrow 0$ as $\theta_{m\mu} \rightarrow \theta_{zmax}$. No sound power is therefore transmitted at cut-off. A good approximation to the effective modal admittance $\hat{\gamma}(\theta)$ plotted in figure 3 versus propagation angle which incorporates this cut-off condition is described by the simple function

$$\hat{\gamma}(\theta) = \cos\left(\tfrac{1}{2}\pi\theta/\theta_{Z\max}\right) \qquad (35)$$

where $\theta_{zmax} = \cos^{-1}(-M_z)$. A cost function approximately proportional to the transmitted sound power is therefore given by

$$J_{\dot{w}} = \sum_{k=1}^{K}\sum_{i=1}^{I}\hat{\gamma}(\theta_i)\left|b(\theta_i, a, \phi_k)\right|^2 \qquad (36)$$

where $\theta_i$ spans the full range propagation angles such that $\theta_i = 0°$ and $\theta_I = \theta_{zmax}$ in some appropriate incremental angle. For completeness, recall that

$$b(\theta_0, a, \phi) = \sum_{l=1}^{L} w_l(\theta_0)p(a, \phi, z_l) \qquad (37)$$

and

$$w_l(\theta_0) = \exp\left\{jl\psi(\theta_0)\right\} \qquad (38)$$

$$\psi(\theta) = \frac{\pi(f/f_{\max})(1 + M_{Z\max})\cos\theta}{1 + M_Z\cos\theta} \qquad (39)$$

An important feature of the cost function of equation (36) is the summation over axial arrays at different azimuthal positions around the duct wall. A cost function based on a single axial line array would, in the

general case. be minimised by rotating various spinning modes to produce destructive interference at the azimuthal location coinciding with the location of the sensor array. Minimising the sum of square outputs from several axial arrays prevents this from occurring and ensures the correct control mechanism by reducing the appropriate modal amplitudes. The number arrays $K$ should be made equal to the number of significant circumferential modal order present in the duct. However. when only a single modal order $m$ is present. is often the case at the comparatively low frequency corresponding to 1BPF. a single axial sensor array is entirely sufficient and $K = 1$.

Reducing sound pressure levels towards the sidelines

In order to reduce by active means the sideline radiation it is necessary to target these radiation angles specifically rather than minimise a global quantity such as sound power. Furthermore. azimuthal directivity of fan noise is generally weak by virtue of the very small number of circumferential modal orders which are able to cut on. Implementing active control in a narrow band of polar radiation angles, but extending the control region to include all azimuthal angles, incurs no appreciable performance penalty. Hereinafter is described a method of how the in-duct error sensor array provides sound pressure level reductions over an axi-symmetric control surface in a band of polar radiation angles. $\Delta\theta$.

The control mechanism underlying the reduction of sideline radiation is made clear by the relationship between the in-duct angles and those in the far field. Tle modes closest to cut-off must be attenuated in order to reduce the sideline radiation. A sketch of the duct. the control surface and axial sensor array configured to control sideline radiation is presented in figure 5 showing an unflanged circular hard walled duct containing a mean subsonic intake flow. Enclosing the duct exit is a sector of a sphere of width $\Delta\theta$ across which the sound power is to be minimised by a ring of secondary sources. A single axial sensor line array at the duct wall detects the transmitted sound field from which the field radiated towards the sidelines can be inferred.

A suitable weighting function on $|b(\theta_i, a, \phi_k)|^2$ which accounts for the importance to sideline radiation of near cut-off modes is the exponential function $\exp\{-\eta(\theta_{zmax}-\theta)\}$. where $\eta$ is an arbitrary constant which specifies the relative weighting assigned to the different modes according to propagation angle. A cost function for reducing sideline radiation incorporating this weighting function is expressed

$$J_{\Delta\Omega} = \sum_{k=1}^{K} \sum_{0>\theta_i>\theta_{zmax}}^{\theta_{zmax}} \exp\{-\eta(\theta_{zmax} - \theta_i)\} |b(\theta_i, a, \phi_k)|^2 \qquad (40)$$

The range of 'look' angles $\theta$ is now taken over the range of propagation angles close to $\theta_{zmax}$ that are most responsible for the sideline radiation. Note. that the summation over different azimuthal axial sensor arrays $K$ is included for generality in order to allow for the presence of a number of different circumferential modal orders $m$.

Claims

1. A duct for fluid flow having means for active control of sound radiated therefrom, said duct comprising sound sensors located on the inner surface of said duct and grouped together in one or more planes transverse with respect to the duct axis, and at least one secondary source whose operation is a function of sound received at said sound sensors characterised in that the axial spacing of said transverse planes is not more than $0.5\lambda_{min}(1 + M_{zmax})$ where $\lambda_{min}$ is the wavelength corresponding to the radiated tone frequency of interest and $M_{zmax}$ is the maximum Mach number of the free stream flow in the duct.

2. A duct as claimed in any of the above claims characterised in that said secondary sources are located on the inner surface of said duct and grouped together in one or more planes transverse with respect to the duct.

3. A duct as claimed in any of the above claims characterised in that the secondary sources are controlled so as to minimise the received sensor signals in a pre-set band of angles to the duct.

4. A duct as claimed in any of the above claims characterised in that the sound sensors have a step response whereby only sound propagated within a pre-set angle to the duct axis is effective sensed and used to control the operation of said secondary sources.

5. A duct as claimed in any of the above claims characterised in that the secondary sources are operatively controlled so as to minimise the sum of squared signals received at the sensors.

6. A duct as claimed in any of the above claims wherein the secondary sources are controlled as a function of the sensors so as to minimise the cost function

$$J = \sum_{i=1}^{I} \sum_{k=1}^{K} \left| b(\theta_{0i}, a, \phi_k) \right|^2 \tag{41}$$

where $b(\theta_{0i}, a, \phi_k)$ denotes the complex signal produced after steering a beam at an angle $\theta_{0i}$ by a receiver array located at the circumferential angle $\phi_k$ around the duct wall and is computed from

$$b(\theta_{0i}, a, \phi_k) = \sum_{l=1}^{L} w_l(\theta_{0i}) p(a, \phi_k, z_l) \tag{42}$$

$$w_l(\theta_0) = \exp\{-jl\psi_0\} \qquad (43)$$

where $\psi_0(\theta_0)$ is the beam steer angle

$$\psi_0 = \frac{\pi(f/f_{max})(1 + M_{Z max})\cos\theta_0}{1 + M_Z \cos\theta_0} \qquad (44)$$

7. A duct as claimed in any of claims 1 to 5 wherein the secondary sources are controlled as a function ofthe sound sources so as to minimise the cost function

$$J_{\psi} = \sum_{k=1}^{K} \sum_{i=1}^{I} \hat{\gamma}(\theta_i) |b(\theta_i, a, \phi_k)|^2 \qquad (45)$$

where

$$\hat{\gamma}(\theta) = \cos(\tfrac{1}{2}\pi\theta/\theta_{Z max}) \qquad (46)$$

$$\theta_{Z max} = \cos^{-1}(-M_Z) \qquad (47)$$

8. A duct as claimed in any of claims 1 to 5 wherein the secondary sources are controlled as a function of the sound sources so as to minimise the cost function

$$J_{\Delta\hat{\Omega}} = \sum_{k=1}^{K} \sum_{0>>\theta_i>\theta_{Z max}}^{\theta_{Z max}} \exp\{-\eta(\theta_{Z max} - \theta_i)\} |b(\theta_i, a, \phi_k)|^2 \qquad (48)$$

$\eta$ is an arbitrary constant

9. A method for the active control of sound radiated from a fluid flow duct comprising:
a) sensing sound from an array of sensors located on the inside surface of the duct and
b) controlling an array of secondary sources located on the inside surface of the duct so as to minimise sound radiated in the far field in a pre-set band of angles to the duct axis. characterised in that only sound propagated within a pre-set angular interval to the duct axis is effectively sensed and used to control the operation of said secondary sources.

10. A method as claimed in claim 9 characterised in that step (b) comprises controlling an array of secondary sources so as to minimise the sum of squared signals received at the sensors within a pre-set angular interval.

11. A method as claimed in claims 9 or 10 characterised in that the secondary sources are controlled so as to minimise the cost function:

$$J = \sum_{i=1}^{I}\sum_{k=1}^{K}\left|b(\theta_{0i}, a, \phi_k)\right|^2 \qquad (49)$$

where $b(\theta_{0i}, a, \phi_k)$ denotes the complex signal produced after steering a beam at an angle $\theta_{0i}$ by a receiver array located at the circumferential angle $\phi_k$ around the duct wall and is computed from

$$b(\theta_{0i}, a, \phi_k) = \sum_{l=1}^{L} w_l(\theta_{0i}) p(a, \phi_k, z_l) \qquad (50)$$

$$w_l(\theta_0) = \exp\{-jl\psi_0\} \qquad (51)$$

where $\psi_0(\theta_0)$ is the beam steer angle

$$\psi_0 = \frac{\pi(f/f_{max})(1 + M_{z\,max})\cos\theta_0}{1 + M_z\cos\theta_0} \qquad (52)$$

12. A method as claimed in claims 9 or 10 wherein the secondary sources are controlled to minimise the cost function:

$$J_w = \sum_{k=1}^{K}\sum_{i=1}^{I}\hat{\gamma}(\theta_i)\left|b(\theta_i, a, \phi_k)\right|^2 \qquad (53)$$

where

$$\hat{\gamma}(\theta) = \cos(\tfrac{1}{2}\pi\theta/\theta_{z\,max}) \qquad (54)$$

$$\theta_{Z\max} = \cos^{-1}\left(-M_Z\right) \qquad (55)$$

13. A method as claimed in claims 9 or 10 wherein the secondary sources are controlled to minimise the cost function:

$$J_{\Delta\Omega} = \sum_{k=1}^{K} \sum_{0 >> \theta_i > \theta_{Z\max}}^{\theta_{Z\max}} \exp\left\{-\eta\left(\theta_{Z\max} - \theta_i\right)\right\} \left|b\left(\theta_i, a, \phi_k\right)\right|^2 \qquad (56)$$

$\eta$ is an arbitrary constant

Fig.1a.

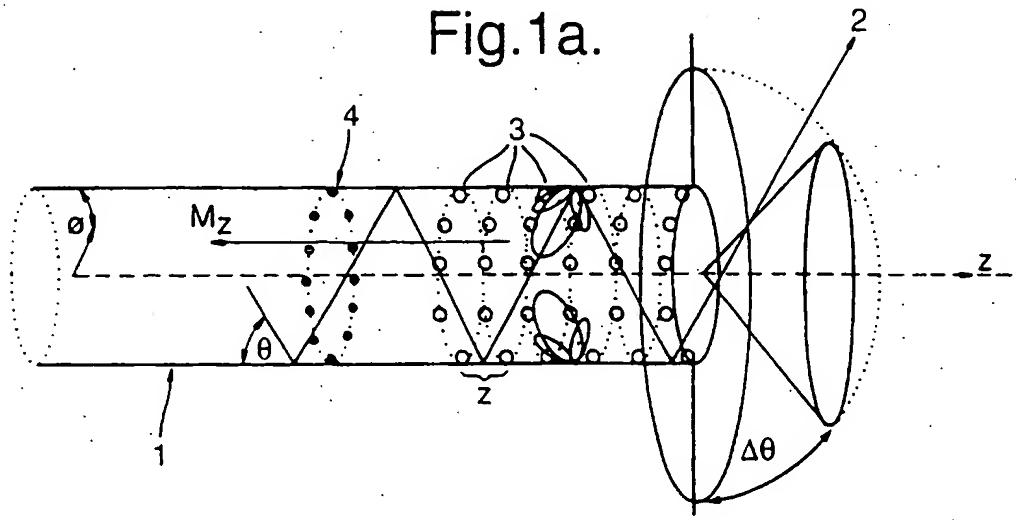



Fig.1b.

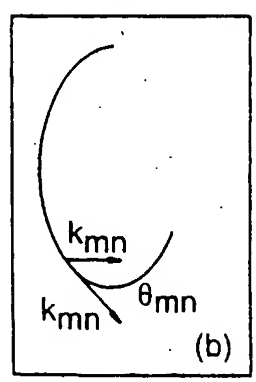


Fig.2.

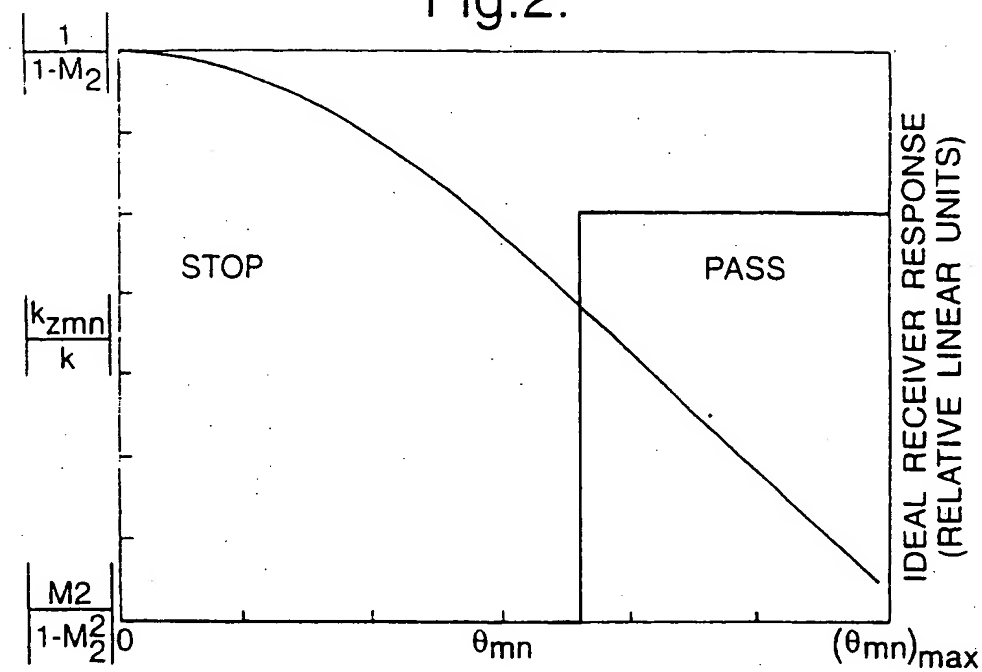

$\frac{1}{1-M_2}$
$\frac{k_{zmn}}{k}$
$\frac{M2}{1-M_2^2}$
STOP
PASS
0
$\theta_{mn}$
$(\theta_{mn})_{max}$
IDEAL RECEIVER RESPONSE
(RELATIVE LINEAR UNITS)

Fig.3.

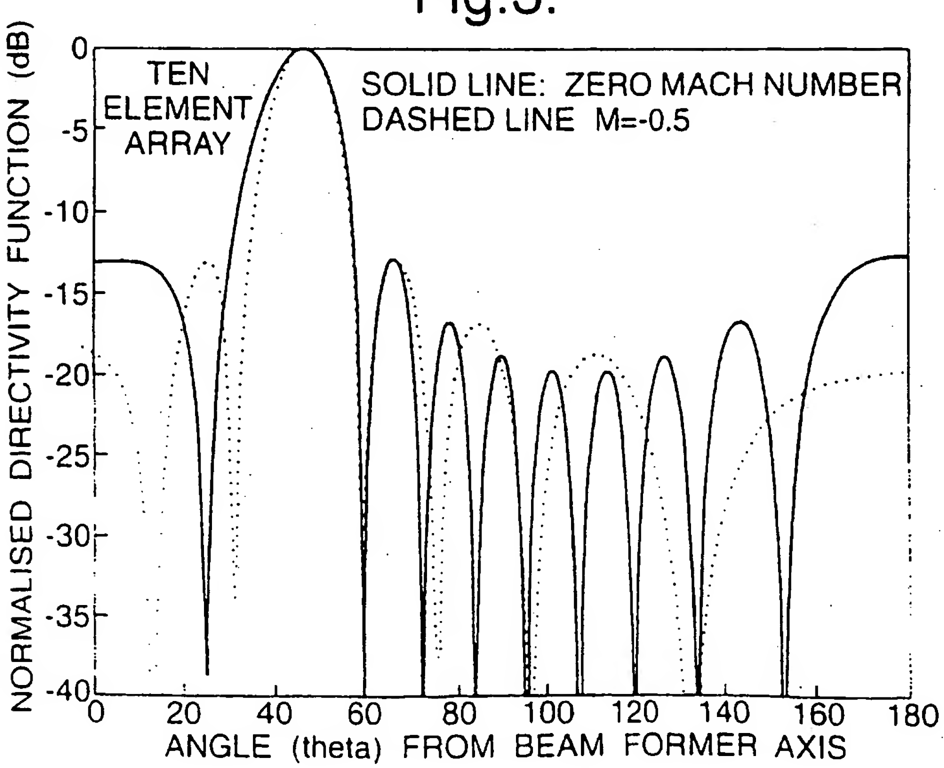

TEN
ELEMENT
ARRAY
SOLID LINE: ZERO MACH NUMBER
DASHED LINE M=-0.5
NORMALISED DIRECTIVITY FUNCTION (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
0
20
40
60
80
100
120
140
160
180
ANGLE (theta) FROM BEAM FORMER AXIS

Fig.4.

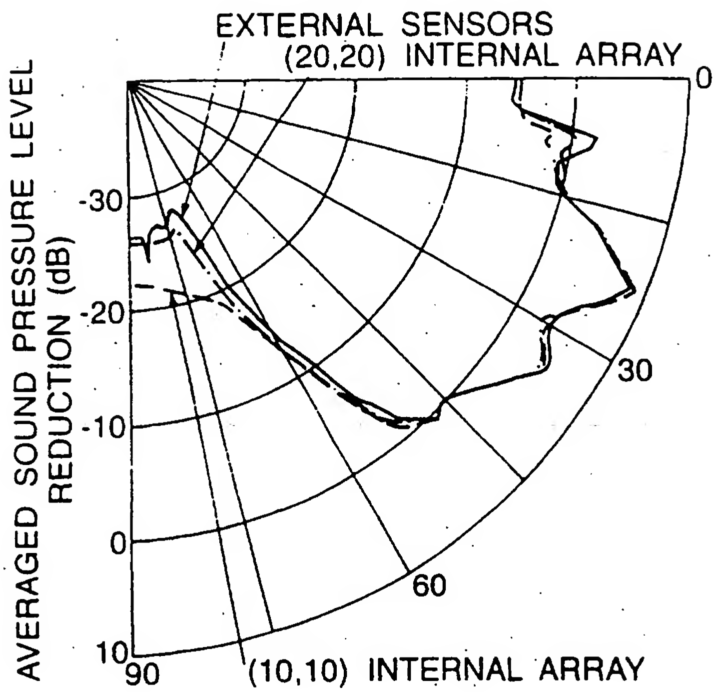
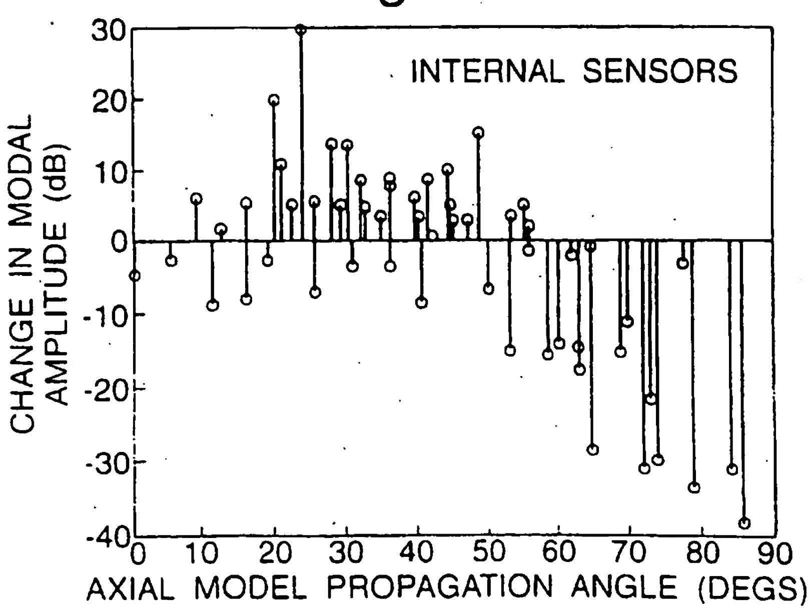



Fig.5.




ka=20 M=0
SOUND POWER REDUCTION = 17.9dB

Fig.6.

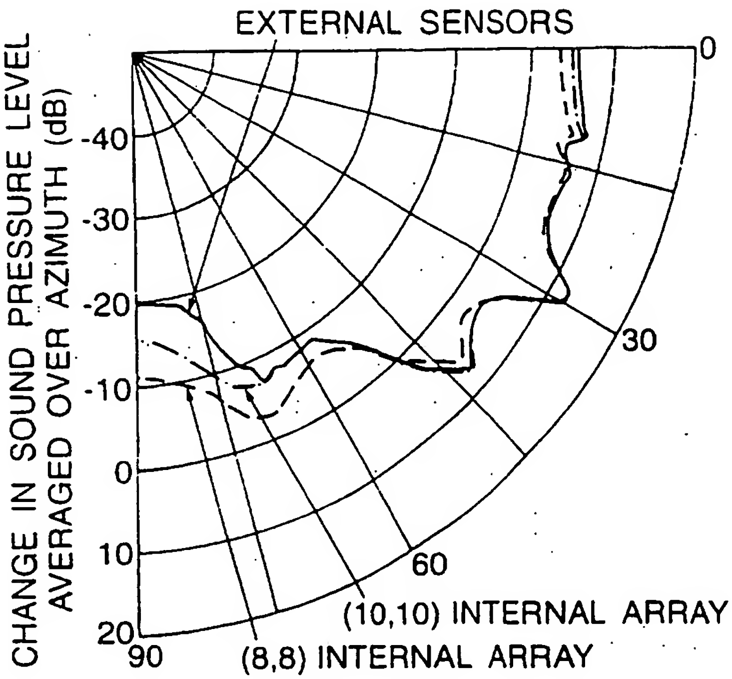
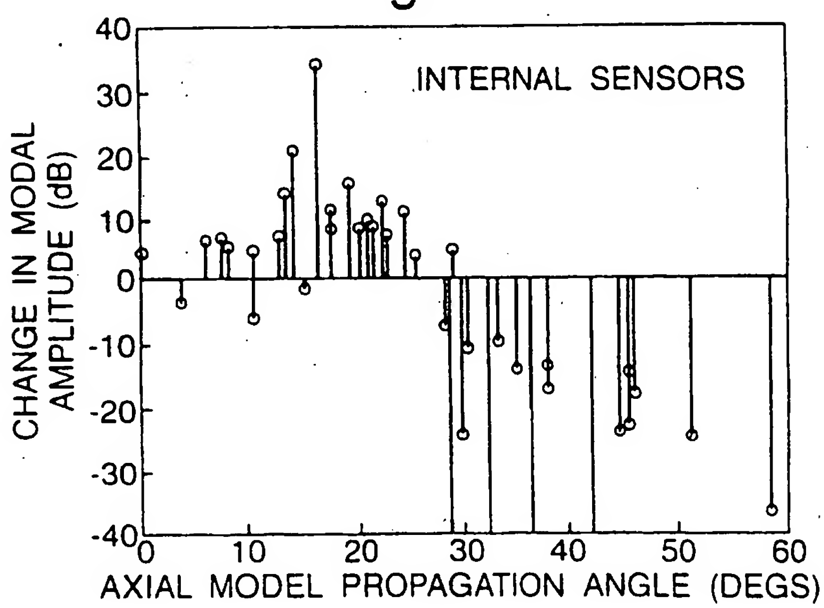



Fig.7.




ka=15 M=-0.5
SOUND POWER REDUCTION = 10.5dB

Fig.8.

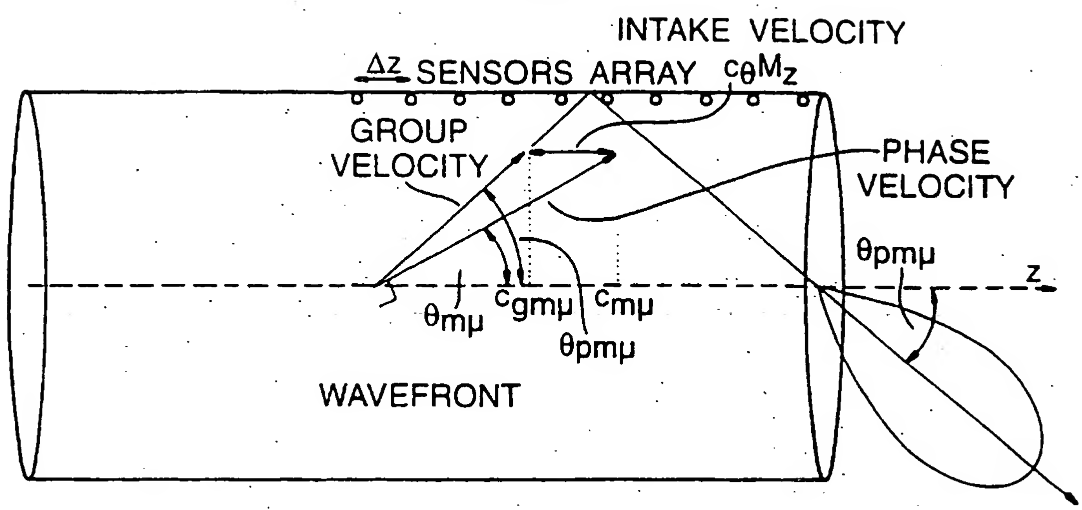
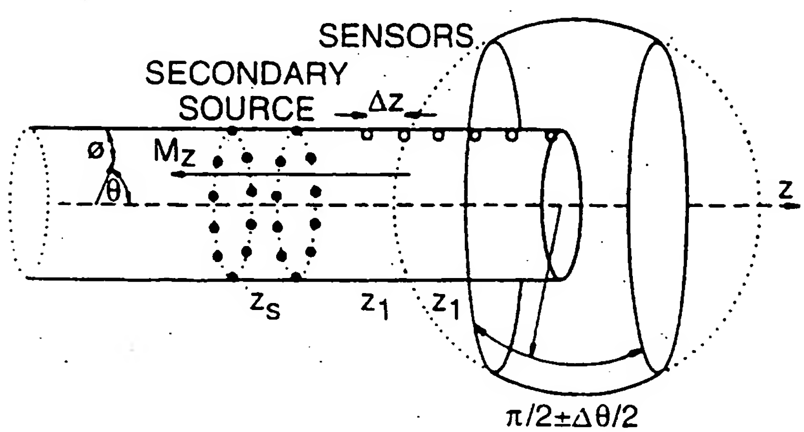

INTAKE VELOCITY
Δz
SENSORS ARRAY
cθMz
GROUP
VELOCITY
PHASE
VELOCITY
θpmμ
z
θmμ
cgmμ
cmμ
θpmμ
WAVEFRONT

Fig.9.


SENSORS
SECONDARY
SOURCE
Δz
ø
Mz
θ
z
zs
z1
z1
π/2±Δθ/2

# INTERNATIONAL SEARCH REPORT

I. ...ational Application No
PCT/GB 97/00624

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 6 G10K11/178

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G10K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category * | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X<br><br>A | US 4 044 203 A (SWINBANKS MALCOLM ALEXANDER) 23 August 1977<br>see abstract<br>see figures 1,4,5,7,8,10<br>see column 4, line 3 - line 55<br>see column 5, line 40 - column 7, line 23<br>see column 8, line 32 - column 9, line 12<br>see column 10, line 34 - column 11, line 56<br>--- | 1-5,9,10<br><br>6,11 |
| X | US 4 171 465 A (SWINBANKS MALCOLM A) 16 October 1979<br>see abstract; figures 1-4<br>see column 1, line 4 - line 56<br>see column 3, line 28 - line 50<br>see column 5, line 10 - line 37<br>see column 5, line 62 - column 6, line 15<br>--- | 1 |

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| Name and mailing address of the ISA<br>European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. ( + 31-70) 340-2040, Tx. 31 651 epo nl,<br>Fax: ( + 31-70) 340-3016 | Authorized officer<br><br>De Heering, P |

# INTERNATIONAL SEARCH REPORT

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

| Category * | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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Information on patent family members

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| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
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